PRECISION MEASUREMENT OF THE HIGGS BOSON MASS AND SEARCH FOR DILEPTON MASS RESONANCES IN H $\rightarrow 4\ell$ DECAYS USING THE CMS DETECTOR AT THE LHC

By

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CHAPTER 1
THE CMS DETECTOR

Figure 1-1. Life-size poster of the CMS detector, taken during CERN Open Days 2019 in the SX5 warehouse where parts of CMS were assembled.

Weighing in at 14 000 tonnes, standing 15 m (5 stories) tall, and reaching 29 m long, the Compact Muon Solenoid (CMS) experiment is one of the four major particle detectors at the LHC (Fig. 1-1). As shown in Fig. 1-2, CMS is situated approximately 100 m under the earth at the fifth collision point (*Point 5*) along the LHC. In 2012, both CMS and its competing experiment, A Toroidal LHC ApparatuS (ATLAS), independently discovered the Higgs boson.

Recall that the LHC (Chapter **??**) directs two proton bunches together on a collision course every 25 ns to produce thousands of new particles per pp collision. These outward-moving particles travel all sorts of directions away from the interaction point. CMS is built around the interaction point in a series of cylindrical subdetectors for nearly hermetic coverage so that most of the particles *must* travel through CMS. The detector sports a solenoid—for which CMS was named—which generates a 3.8 T uniform magnetic field that points longitudinally down the central axis of CMS. This strong magnetic field applies a Lorentz force on the outgoing charged particles, causing them to follow helical, momentum-dependent trajectories. These curved tracks separate from one another which assists in particle identification. Electrically neutral particles experience no Lorentz force and thus travel in straight lines.

The subdetectors measure the properties of the outgoing particles and carefully filter them out in a clever way (Fig. 1-3). As particles pass through the subdetectors, they interact in a variety of ways. For example, charged particles can leave "hits" in the silicon tracker system and continue through to the next radially outward subdetector, whereas hadronic matter tends to be captured by the hadronic calorimeter. Generally, hits can be reconstructed into particle tracks. From the track curvature, the charge and momentum of the particles can be deduced. Depending on *which* subdetector (or combination of subdetectors) produced signals, the type of particle can be deduced. A few example particles and their associated tracks are shown in Fig. 1-4.

Before discussing each subdetector in the following sections, it is useful to define the coordinate system used in CMS; a typical, right-handed, three-dimensional Cartesian coordinate system (x, y, z) is chosen, whose center $(0, 0, 0)$ is placed at the nominal pp collision point within CMS. The x axis points towards the center of the LHC, the y axis points vertically upward, and the z axis points westward towards the Jura mountains, tangential to the beam direction. Since CMS covers almost the entire spherical 4π steradians around the interaction point, it is convenient to use spherical coordinates (r, ϕ, θ), in which r measures the radial distance in the x-y plane, ϕ measures the azimuthal angle in the x-y plane as measured from the x axis, and θ measures the polar angle as measured from the z axis. When dealing with ultra-relativistic particles like those produced at the LHC, special-relativistic effects like length contraction must be taken into account and so the coordinate θ becomes frame-dependent. It is thus helpful to convert θ to the Lorentz-invariant quantity called pseudorapidity (η), defined as $\eta = -\ln[\tan(\theta/2)]$.

In the remainder of this chapter, the subdetectors of CMS are described in detail: the silicon tracker in Sec. 1.1, followed by the electromagnetic and hadron calorimeters in Sec. 1.2, then the solenoid and yoke system in Sec. 1.3.

1.1 The Silicon Tracker

At the heart of CMS is one of the world's largest silicon detectors: the silicon tracker. The main goal of the silicon tracker is not to capture outgoing particles but to very precisely measure the hits from the charged particles as they pass through it. The tracker also assists in vertex identification, differentiating between primary and secondary vertices, the latter of which often comes from B meson decays. When multiple pp collisions occur within the same BX (so-called *pile up*), the tracker distinguishes between proton collisions with a resolution of about 100 μm longitudinally and 50 μm transverse to the beam pipe. This is crucial to resolve which outgoing particles came from which pp vertex.

The tracker consists of two types of pure silicon detectors: the pixel detector and the strip detector, each of which is described in turn below.

1.1.1 The Pixel Detector

The innermost part of the silicon tracker is the pixel detector, which is the closest subdetector to the interaction point. The pixel detector is composed of 66 million silicon "pixels", as shown in Fig. 1-5 (Left, pink). A single pixel is $100\,\mu\mathrm{m} \times 150\,\mu\mathrm{m}$ and, collectively, they cover a sensitive area of $1.9\,\mathrm{m}^2$. Because it sits only 8 cm away from the beam pipe, the pixel detector receives the highest particle flux than any other subdetector: around 10 million particles/cm^2 per second.

The pixel detector is made of three cylindrical layers and two endcaps that surround the beam pipe. In total, the pixel detector has around 6,000 connections (channels) per cm^2.

After the LHC Run 1 was completed, the accelerator received luminosity upgrades during the 2013–2014 Long Shutdown. To handle these higher luminosities, the pixel detector was replaced by the CMS Phase-1 pixel detector during the LHC technical stop in 2016–2017. The upgrades outfitted the detector with four barrel layers and three endcap disks per side, which allowed for particle detection up to $|\eta| < 2.5$. The overall mass of the pixel detector decreased and granted the detector with better tracking capability.

1.1.2 The Strip Detector

The outer part of the silicon tracker is called the strip detector, which has 10 million detector strips spread across 10 cylindrical layers. The first 4 layers belong to the tracker inner barrel (TIB) and the remaining 6 layers belong to the tracker outer barrel (TOB), Fig. 1-5 (Left, green and blue, respectively). Both the TIB and TOB have two endcaps associated with them, the TID and TEC, respectively. Accounting for all of its components, the strip detector is sensitive to $200\,\mathrm{m}^2$.
Fig. 1-6 gives a clearly labelled transverse illustration of the pixel and strip detectors.

1.2 The Calorimeters

1.2.1 Electromagnetic Calorimeter

Overview: Particles that pass through the silicon tracker 1.1 encounter the electromagnetic calorimeter (ECAL). Those particles which interact electromagnetically but not strongly (i.e., mostly photons and electrons) are typically absorbed by the ECAL. The particle's energy is then transferred to the ECAL in the form of an electromagnetic (EM) shower. The size and shape of the EM shower provide information about the particle's energy and trajectory. Since the Higgs boson can decay into two photons, the ECAL played a critical role in detecting this decay mode.

Design: The ECAL is a hermetic, cylindrical, homogeneous sub-detector that consists of a barrel (EB), two endcaps (EE), and a preshower detector in front of each endcap (Figure 1-7, Left). The EB covers $|\eta| < 1.479$ while the EE covers $1.479 < |\eta| < 3.0$. The entire subdetector is composed of transparent lead tungstate ($PbWO_4$) crystals that point axially towards the center (i.e., towards the interaction point) of CMS. The transparent crystals, one of which is shown in Fig. 1-8 (Left), have a high density (8.28 g/cm^3) which provides the ECAL with radiation resistance and a short radiation length ($X_0 = 0.89\,\text{cm}$). Because so many crystals are used (61 200 crystals in the EB and 7324 in the EE), the ECAL has excellent energy resolution and fine granularity. Each endcap is composed of two *Dee*s, one of which is shown in Figure 1-7 (Right). A single Dee carries 3662 crystals. Crystals in the barrel are tapered, having front-face dimensions $2.2\times2.2\,\text{cm}^2$, back-face dimensions $2.6\times2.6\,\text{cm}^2$, and are 23.0 cm long (25.8 X_0). Crystals in the endcaps are also tapered, with front-face dimensions $2.862\times2.862\,\text{cm}^2$, back-face dimensions $3.0\times3.0\,\text{cm}^2$, and are 22.0 cm long (24.7 X_0). This gives a single crystal from the barrel a volume of approximately 132.5 cm^3 (i.e., 132.5 mL)—about the volume of a small cup of coffee—yet it has a surprisingly hefty mass of 1.5 Kg [1].

Physics: When electrons or photons pass through the ECAL, they create an EM shower. Electrons radiate more photons as they accelerate around $PbWO_4$ nuclei, in a process called *bremsstrahlung*. Meanwhile, near the presence of a nucleus, high-energy photons pair produce into e^+e^-. This cycle of electron/photon production disperses all the initial particle energy into a spray of decreasingly lower-energy particles until it all runs out; this is the EM shower.

The ECAL crystals then scintillate (emits photons) in proportion to the amount of energy deposited by the interacting particle. The scintillator photons are detected by avalanche photodiodes on the back of each barrel crystal or by vacuum phototriodes in the endcap crystals (Fig. 1-8, Right). After 1 BX (25 ns), approximately 80% of the scintillated light is emitted.

An energy deposit in the ECAL could come from either an electron or a photon. In order to tell the difference, information from the silicon tracker is used. Charged particles, like electrons, will leave hits in the tracker and follow a curved path, whereas photons are electrically neutral and thus will not show any signs within the silicon tracker. So long as the tracker and ECAL communicate effectively with each other, then they help distinguish between electrons and photons. Charged hadrons interact only minimially with the ECAL, instead continuing on to the Hadron Calorimeter. Neutral hadrons can be detected by the ECAL preshower near the ECAL endcaps which helps distinguish a single photon from π^0 mesons as they decay into two photons with a narrow opening angle, making it look as if the two photons are a single photon. The preshower detector allows CMS to distinguish between collimated, low-energy diphoton pairs and single high-energy photons.

From the original spray of particles that leave the interaction vertex, the short-lived particles have decayed into lighter, more stable, particles and the ECAL has filtered out most of the electrons and photons. The remainder of the spray is comprised of both hadronic matter and muons, however the hadrons are many times more numerous than the muons and so are filtered out next.

1.2.2 Hadron Calorimeter

Overview: The particles that survive the ECAL—typically only muons and hadrons—then enter the hadron calorimeter (HCAL). Its primary purpose is to absorb the hadronic matter emerging from the interaction point and to measure the corresponding jet energies. The absorbed jets cause the HCAL to scintillate photons which are then converted into electrical signals. These signals help deduce the original jet energies and missing transverse energy ($E_{\mathrm{T}}^{\mathrm{miss}}$) from the event.

Design: Dissimilar to the ECAL (Sec. 1.2.1) in material composition but similar to it in shape, the HCAL is a brass cylindrical scintillator. Although it has a barrel (HB) and two endcaps (HE), it has two more detectors than the ECAL: the outer calorimeter (HO) and the forward calorimeter (HF). The HB spans the pseudorapidity range $|\eta| < 1.3$, the HE spans $1.3 < |\eta| < 3$, and the HF spans $3 < |\eta| < 5.2$, as shown in Fig. 1-9. With a thickness of over 1 m, the HB is sandwiched between the barrels of the ECAL and the solenoid (Sec. 1.3) at radial values $r = 1.77\,\text{m}$ and $r = 2.95\,\text{m}$, respectively. Because the HB and HE are located within the solenoid's strong magnetic field of 3.8 T, they were both constructed out of a non-magnetic absorber called *C26000 cartridge brass*. This absorber has a density of $8.53\,\text{g/cm}^3$ and an interaction length (λ_I) of 16.42 cm. The thickness of the HB increases as $1/\sin\theta$ so that at $|\eta| = 0(1.3)$ the absorber thickness is $5.82(10.6)\ \lambda_I$. The HB is composed of two half-barrels, where each half-barrel is built from 18 identical azimuthal wedges and each wedge spans 20°. Each wedge is divided into four ϕ segments so that a single ϕ segment spans $\Delta\phi = 0.087$.

Since the volume available to the HCAL is so limited—and in order to stop any particles that might traverse the entire HCAL and solenoid—the HO (the *tail catcher*) is situated outside the barrel of the solenoid. The HF is located 11.2 m from the interaction point. All tiles within a single ϕ segment are grouped together into a single tray unit. The scintillator is also segmented into 16 η sectors, the first(last) of which is located at $|\eta| = 0(1.3)$. This way each tile covers $(\Delta\eta, \Delta\phi) = (0.087, 0.087)$. Each layer has 108 trays.

Physics: Since hadrons are the only particles to interact via the strong force, the HCAL is designed to have a high nuclear density. This ensures ample opportunity for hadrons to radiate gluons and convert with the Similar to the ECAL, the HCAL will scintillate in proportion to the amount of energy of the captured particle. The incoming hadrons will *hadronize* (i.e.,, produce a hadronic shower), generating jets of quarks and gluons which are bound in various ways forming protons, neutrons, pions, kaons, etc. Interestingly, the HCAL is made using over a million old, brass shell casings from the Russian Navy back from World War II.

About 34% of the particles produced from LHC pp collisions enter the HE region, so the

HE was built to handle high rates (MHz).

The entire HCAL utilizes approximately 70,000 plastic scintillator tiles. The active material in the HB is 3.7- mm-thick Kuraray SCSN81 plastic scintillator, selected for its radiation hardness and long-term stability. Hadron showers -> tiles scintillate -> scintillated photons are collected by 0.94- mm-diameter green double-cladded wavelength shifting (WLS) fibers (Kuraray Y-11), which carry the light to hybrid photodiodes (HPD).

1.3 The Solenoid and the Steel Return Yoke

The Compact Muon *Solenoid* sports one of the world's most energetic solenoids which is paramount to the success of CMS. Particles that exit the HCAL (subsec. 1.2.2) arrive at the cylindrical magnet which is 12.5 m in length, has a bore diameter of 6 m (6.3 m when cold), and generates a uniform 3.8 T magnetic field parallel to the beam line. To produce such a large and uniform magnetic field inside the approximately 360 m^3 volume (Fig. 1-10), an 18 000 amp current travels through the 4-layer, superconducting, NbTi coils. This magnetic field stores a massive 2.6 GJ of energy—approximately the kinetic energy of an Airbus A320 in flight—and is 100 000 times stronger than Earth's magnetic field, as measured on the surface. The magnet has such a large stored-energy-to-cold-mass ratio (11.6 KJ/Kg) that it experiences a physical deformation of 0.15% while being energized.

As charged particles travel through any magnetic field, they experience a magnetic (Lorentz) force perpendicular to their direction of travel. The Lorentz force $\left(\vec{F}_B\right)$ exerted on a particle with charge q depends on the particle's velocity ($\vec{v}$) and the magnetic field $\left(\vec{B}\right)$ via the cross product

$$\vec{F}_B = q\vec{v} \times \vec{B}.$$

Since the force is necessarily perpendicular to the velocity, the resulting trajectory is helical. Projecting the helix on the x-y plane (since the magnetic field points in the $+z$ direction) allows the particle tracks to typically be separated from one another. Each track has a corresponding radius of curvature (R) which relates to its transverse momentum (p_T) through

$$p_\mathrm{T} = qBR.$$

The relative change in p_{T} (i.e., the *momentum resolution*) is given by

$$\frac{\delta p_{\mathrm{T}}}{p_{\mathrm{T}}} \propto \frac{p_{\mathrm{T}}}{BL^2}. \tag{1-1}$$

Steel Return Yoke: Most of the mass of CMS comes from the *steel return yoke* which helps to redirect the magnetic field back on itself. The yoke system constitutes 10 000 tonnes, which is 89% of the total mass of CMS. It is comprised of 5 wheels and 2 endcaps.

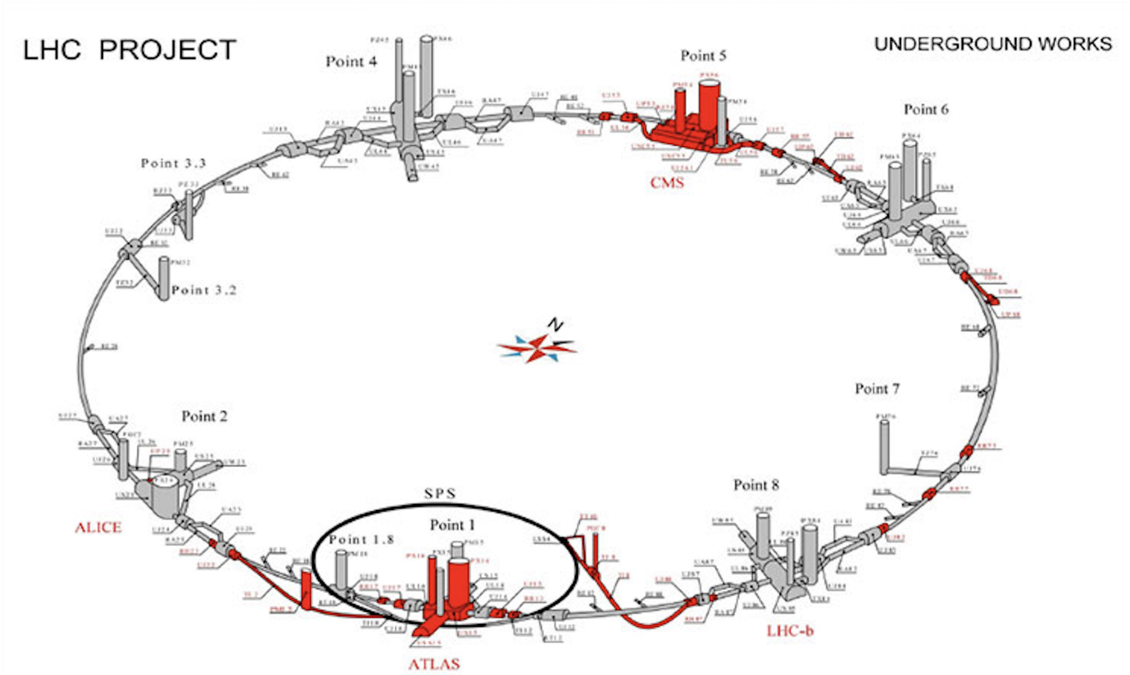

Figure 1-2. Points of interest along the LHC (Points 1–8). Collisions occur at Points 1 (ATLAS), 2 (ALICE), 5 (CMS), and 8 (LHCb), whereas the remaining points are used for LHC beam maintenance and testing.

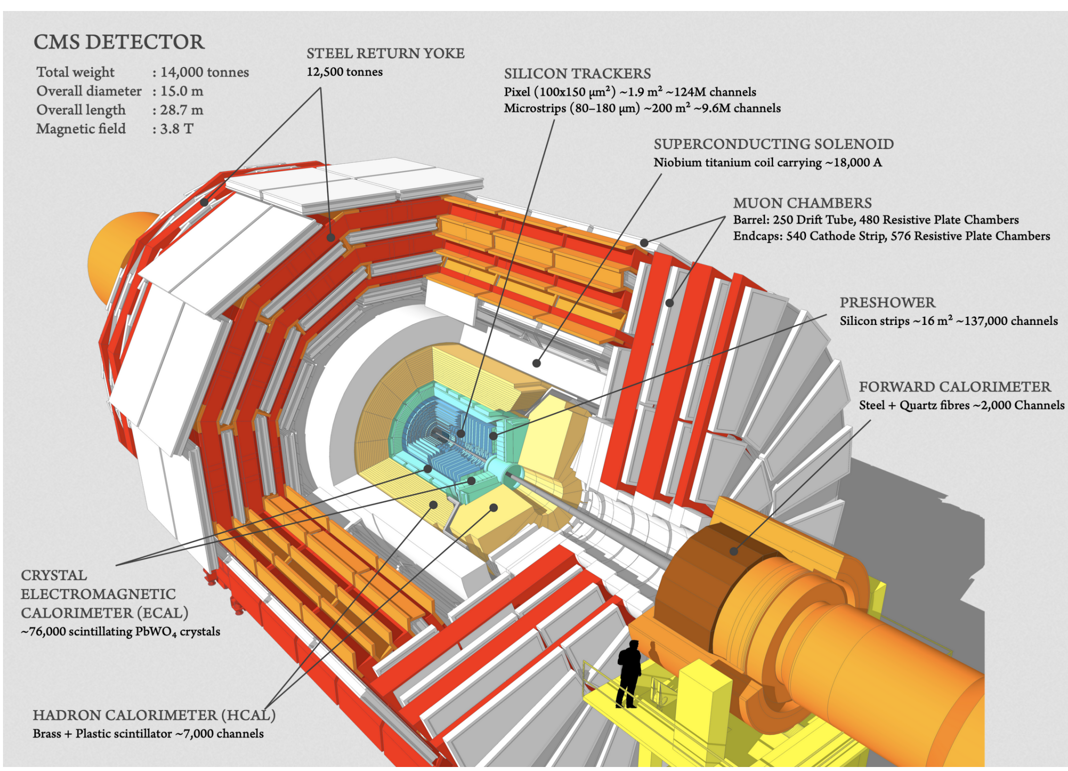

Figure 1-3. Cut out of the CMS detector showing its various subdetector components.

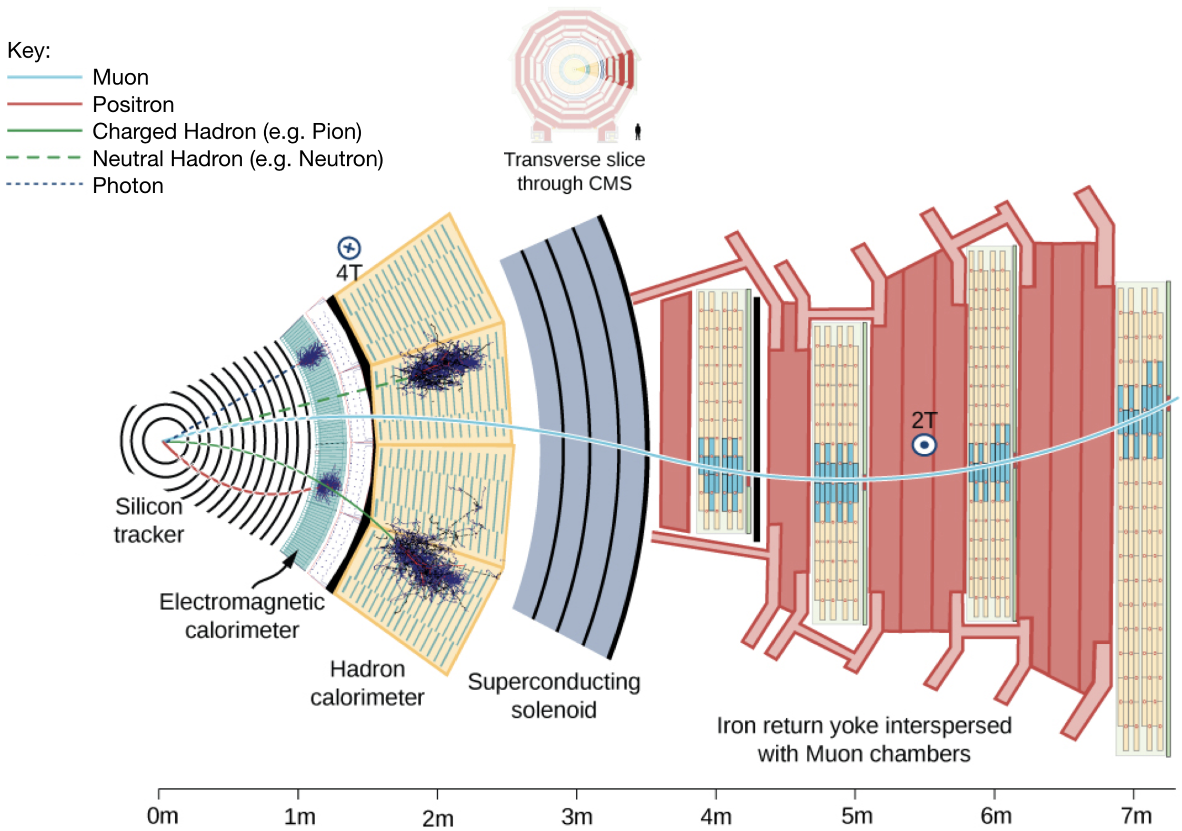

Figure 1-4. A transverse view of CMS showing the "filtration process" as different particles pass through different subdetectors. A positron (solid red line) curves due to the presence of the magnetic field and gets stopped in the ECAL, creating an EM shower. A photon (blue dashed line) does not get detected at all by the Silicon Tracker, since it has no electric charge. It continues through to the ECAL and makes a shower here, like the positron. Charged hadrons (solid green line) will show curved tracks from the Silicon Tracker, may leave some trace in the ECAL, but primarily get stopped by the HCAL creating hadronic showers. Neutral hadrons (dashed green line) do not interact with the tracker, and only undergo EM showers a little in the ECAL, but show most energy deposits in the HCAL. Muons (solid blue line) are detected by the Silicon Tracker and then mostly pass through the other subdetectors without interacting until they finally reach the Muon System. Using the Lorentz force law and knowing which direction the magnetic field is pointing, one can deduce the sign of the charge of the particle. Based on the radius of curvature from the trajectory, one can then calculate the momentum and energy of the particle.

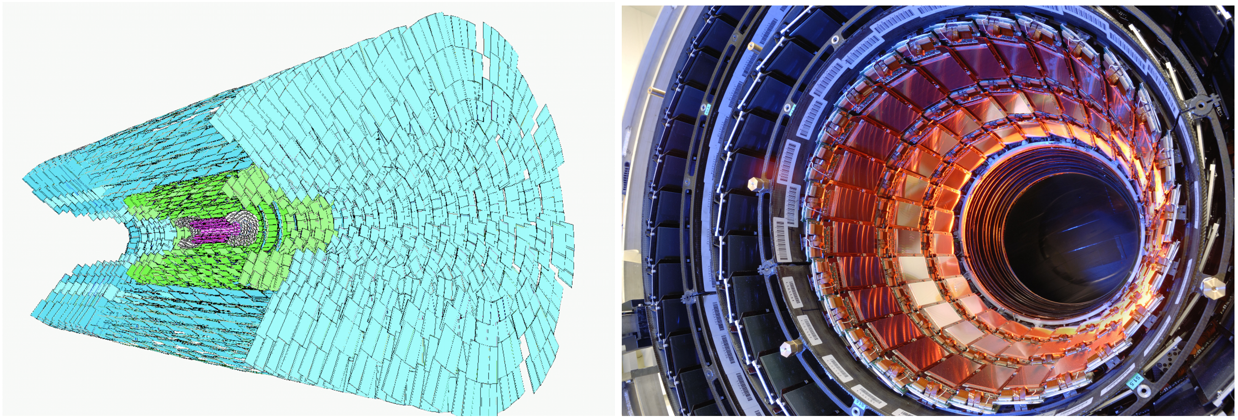

Figure 1-5. (Left) A simulation of the silicon tracker, showing the 3 cylindrical layers of the pixel detector (pink), 4 layers of the TIB (green), and the 6 layers of the TOB (blue) of the strip detector. The endcap components are also shown. (Right) A picture of the real silicon tracker at the center of CMS.

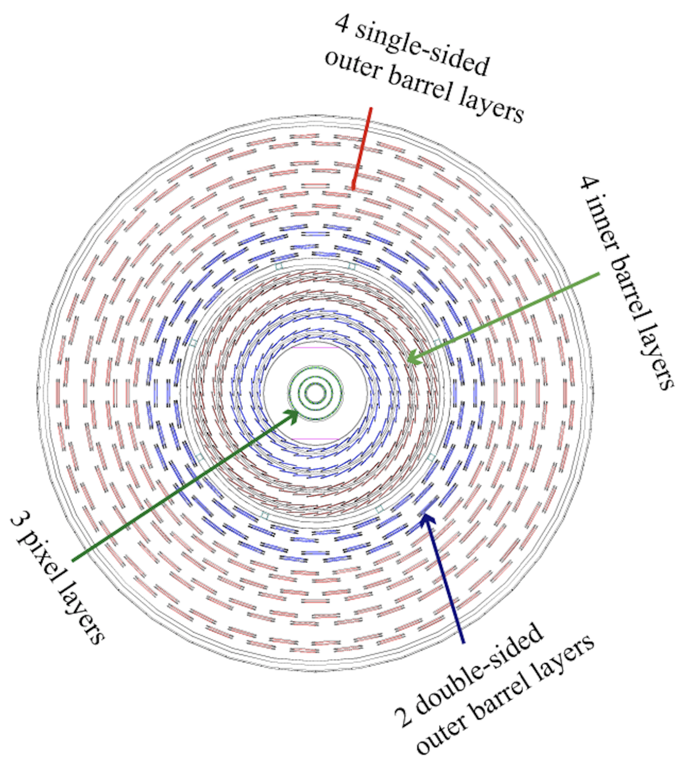

Figure 1-6. A transverse view of the silicon pixel and strip detectors, explicitly labelling the different layers involved.

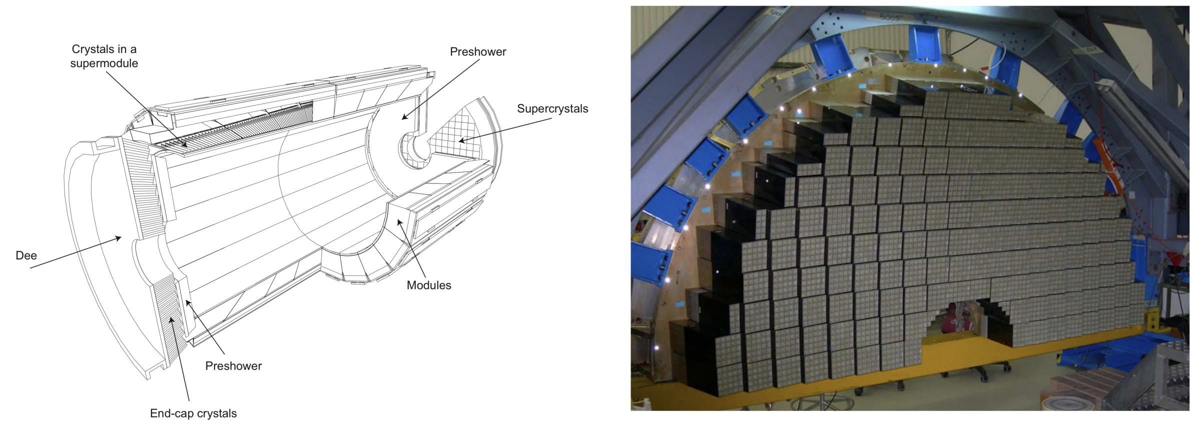

Figure 1-7. (Left) Cross-sectional view of the electromagnetic calorimeter of CMS. (Right) One of the Dees which comprise the EE. Each square of 5×5 crystals constitutes a "supercrystal". Figure taken from Ref. [2].

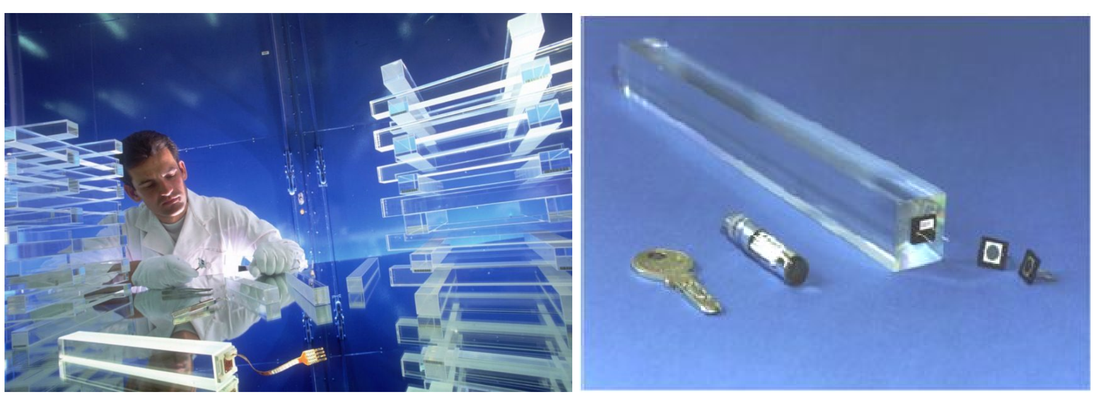

Figure 1-8. (Left) ECAL crystals made from $PbWO_4$ are grown in a lab. (Right) Although made mostly of metal, ECAL crystals are transparent and have a photomultiplier detector attached at the end.

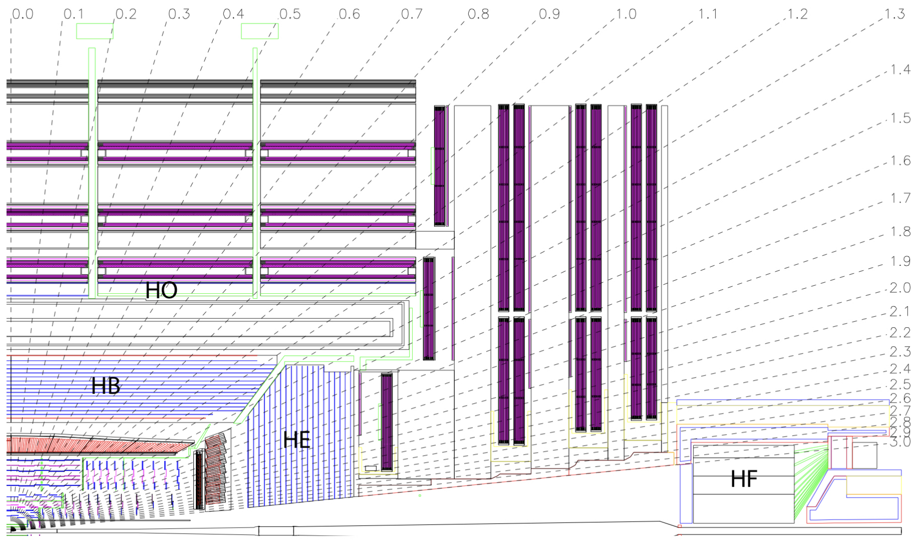

Figure 1-9. A cross-sectional quadrant view of CMS showing the locations of the HCAL components: the barrel (HB), outer (HO), endcap (HE), and forward (HF) detectors.

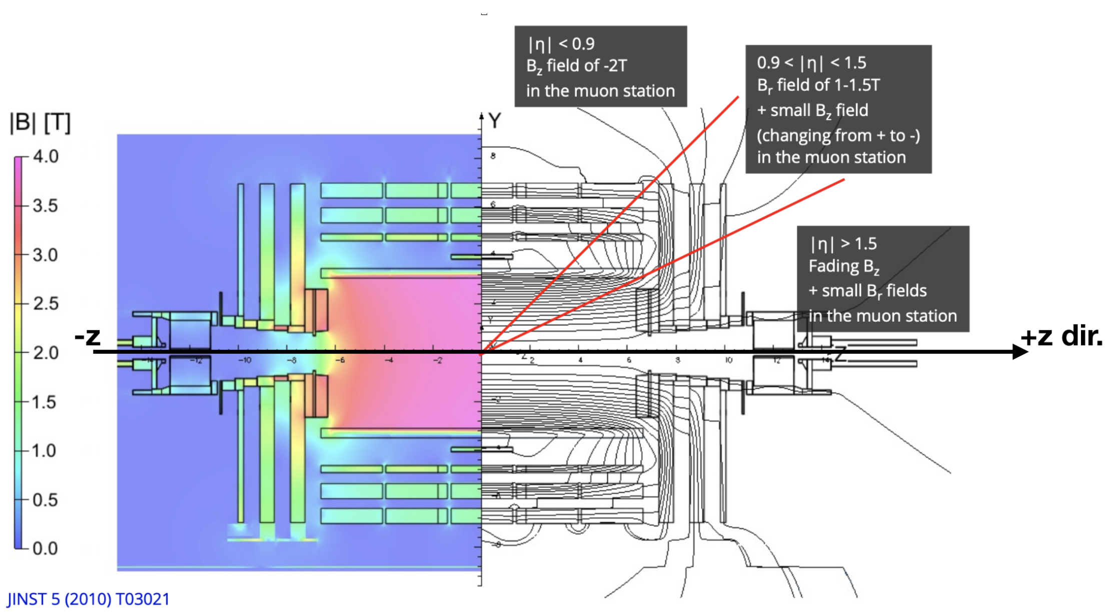

Figure 1-10. A longitudinal cross section of CMS showing the values of the magnetic field over the volume of CMS and various field lines. The magnetic field reaches its maximum of 3.8 T in the center of the detector.

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[2] CMS collaboration, *The CMS experiment at the CERN LHC*, *Journal of Instrumentation* **3** (2008) S08004.